Für Herrn

Symposium on the Canary Current:
Upwelling and Living Resources

81: Sediments in upwelling areas, particularly off Northwest Africa

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Fig. 1

NW African continental margin standard profiles: Geological Institute, Kiel University, cruises with F. S. "Meteor" (8-1967, 25-1971, 39-1975) and RFS "Valdivia" (1975)

1-5 = Types of natural vegetation and climates.

1 Mediterranean scrub: Temperate-warm, summer dry, winter rainy.

2 Steppe: Hot, summer dry.

3 Desert: Hot, dry.

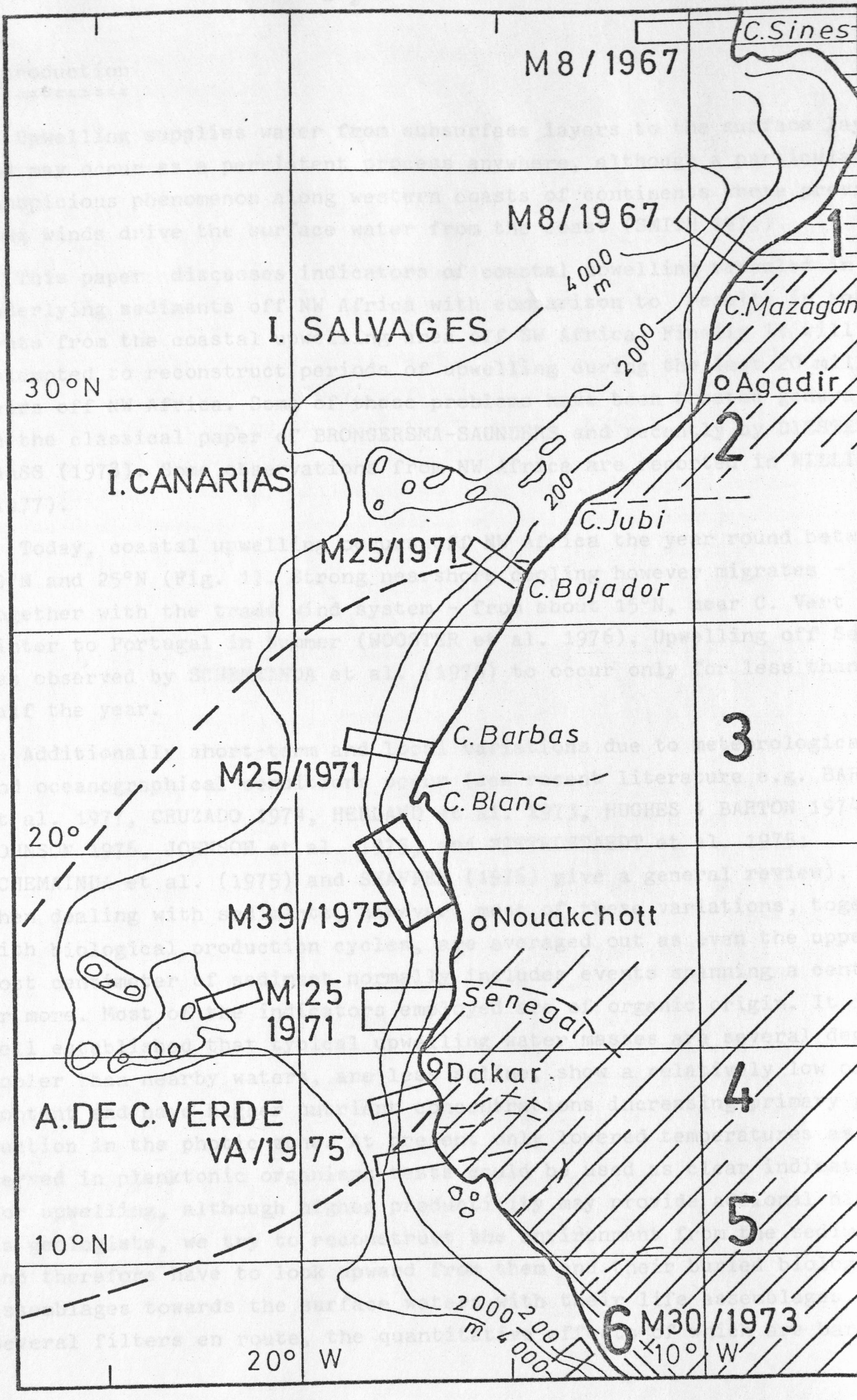
4 Steppe: Hot, winter dry.

5 Savannah: Tropical, winter dry.

6 Tropical rain forest: Hot, humid

Dashed boundary indicates central area of dust falls during winter.

Fig. 1


C.Sines
M8/1967
M8/1967
1
4000 m
C.Mazagan
I. SALVAGES
2000
Agadir
30°N
2
I.CANARIAS
200
C.Jubi
M25/1971
C.Bojador
C.Barbas
3
M25/1971
C.Blanc
20°
M39/1975
Nouakchott
M 25
1971
Senegal
Dakar
4
A.DE C.VERDE
VA/1975
5
10°N
2000
200
m
4000
6
M30/1973
10° W
20° W

Introduction

Upwelling supplies water from subsurface layers to the surface layer and may occur as a persistent process anywhere, although a particularly conspicious phenomenon along western coasts of continents where prevailing winds drive the surface water from the coast (SMITH 1973).

This paper discusses indicators of coastal upwelling revealed in the underlying sediments off NW Africa with comparison to results in sediments from the coastal upwelling area off SW Africa. Finally it will be attempted to reconstruct periods of upwelling during the last 20 million years off NW Africa. Some of these problems have been treated generally in the classical paper of BRONGERSMA-SAUNDERS and recently by DIESTER-HAASS (1978). Some observations from NW Africa are reported in MILLIMAN (1977).

Today, coastal upwelling occurs off NW Africa the year round between 20°N and 25°N (Fig. 1). Strong nearshore cooling however migrates - together with the trade wind system - from about 15°N, near C. Vert in winter to Portugal in summer (WOOSTER et al. 1976). Upwelling off Senega was observed by SCHEMAINDA et al. (1975) to occur only for less than half the year.

Additionally short-term and local variations due to meteorological and oceanographical conditions occur (see recent literature e.g. BARTON et al. 1977, CRUZADO 1974, HEBLAND et al. 1973, HUGHES & BARTON 1974, JOHNSON 1976, JOHNSON et al. 1975, and MITTELSTAEDT et al. 1975; SCHEMAINDA et al. (1975) and SHAFFER (1976) give a general review). When dealing with sediments, however, most of these variations, together with biological production cycles, are averaged out as even the uppermost centimeter of sediment normally includes events spanning a century or more. Most of the indicators employed are of organic origin. It is well established that typical upwelling water masses are several degrees cooler than nearby waters, are less saline, show a relatively low oxygen content and have higher nutrient concentrations increasing primary production in the photic zone. At present only lowered temperatures as preserved in planktonic organisms tests could be used as clear indicators for upwelling, although higher productivity may provide addional hints. As geologists, we try to reconstruct the environment from the sediments and therefore have to look upward from them and their buried biological assemblages towards the surface waters with their life assemblages. Several filters en route, the quantitative effects of which are barely known, alter or even destroy environmental indicators (see general discussion in BERGER 1976).

Filter problems

All suspended particles have to pass several filters between the surface waters and their incorporation into marine sediments. Most of the effects pertinent to our problem depend on the duration of this transfer.

Midwater filter

Settling rates depend on sizes and shapes of particles and may reach more than 2000 m day^{-1} (empty pteropods, planktonic foraminifera). Rates for diatom frustules or coccolithophore plates around 10 m day^{-1} have been reported (BERGER 1976, SEIBOLD 1978). Even unidirectional, continuous currents with velocities up to 4 cm sec^{-1} throughout the water column would result in lateral shifts of indicators from planktonic foraminifera of only a few kilometers at continental margins. Smaller particles could be laterally transported some tens of kilometers, however many of them are incorporated in faecal pellets with settling rates of some 100 meters day^{-1}. Downwelling may accelerate sinking, while upwelling and pycnoclines (BISHOP et al. 1977) retard sinking. Nevertheless this lateral translation is neglible for our biological indicators in continental margin depths.

Long transfer times of small particles, however, are important for chemical effects. Higher temperatures and lower silica concentrations within the uppermost few hundred meters ("silica corrosion zone," BERGER 1976) are responsible for dissolution of empty thin-walled diatom tests as observed by RICHERT (1975), MILLIMAN (1977) and measured by NELSON & GOERING (1977) off NW Africa, although they may partly bypass this filter if contained within faecal pellets (SCHRADER 1971, 1972). Dissolution of aragonite (pteropods) and calcite (foraminifera, coccoliths) occurs in deeper waters and only a small percentage of these tests may be damaged or lost during settling. SAIDOWA (1968) observed well preserved planktonic calcite tests in gut contents of benthic organisms living in water depths of more than 4000 m. BERGER & PIPER (1972) calculated some loss values after field experiments.

Predators may damage tests mechanically, but protect them chemically in faecal pellets.

Bottom water filter

Waves and currents normally affect the sea bottom on the shelf with maximal effects. Erosion and non-deposition is reported from many areas off NW Africa (EINSELE et al. 1977, MASSE 1968, McMASTER & LACHANCE 1969, NEWTON et al. 1973, SUMMERHAYES et al. 1972, 1976). All signs of present upwelling are absent there, while in many other areas fine particles together with most of our indicators are winnowed out or damaged within the sands or coarser materials. Reworking mixes indicators of different periods and areas. Therefore we concentrated our sedimentological investigations on slope and rise stations hoping that particles indicating upwelling reach these regions directly from mixed surface waters extending 50-100 km offshore or by near-bottom downslope transport. The latter can be proved by small amounts of glauconite, shelf relict material, thick shelled benthonic pelycopods and benthonic foraminifera from shallow water incorporated in surface sediments on the slope and rise (DIESTER-HAASS 1975, BEIN & FÜTTERER 1977, LUTZE, in press, LUTZE et al., in press).

Poleward-flowing contour currents in water depths between about 100 and 600 m were observed on the NW African slope from Senegal up to C. Bojador (JOHNSON et al. 1975, MITTELSTAEDT 1976). In 150-200 m water depths daily mean speeds of 7-20 cm sec^{-1} were measured. Therefore we have to consider transport and sorting effects. From a mixture of planktonic foraminifera and radiolarians the latter may be partly winnowed out for example. As mentioned above, sinking of most biogenic particles in the water column lasts several days to weeks. On the seabottom they are exposed to near-bottom waters for several years, dependent on sedimentation rates and bioturbation. Therefore dissolution effects increase partly in a dramatical way. In general, below 1-3 km at present no aragonitic tests are preserved (ACD = Aragonite Compensation Depth) but fragmentation by dissolution begins in even shallower depths. Off NW Africa the Calcite Compensation Depth (CCD) is recorded at about 5 km (BERGER 1976), but dissolution again begins at shallower depths (within the range of the "lysocline"). Carbonate dissolution there depends partl on the content of organic material together with the sedimentation rate. Bacterial decomposition of organic matter produces CO_2 and therefore an upward HCO_3^- concentration gradient, a driving mechanism for the escape of these ions across the water/sediment interface. Carbonate particles can be dissolved there by this mechanism or directly by near-bottom seawater if not protected by a sediment input, covering them.

Dissolution of opaline silica on the sea bottom may be even more effective. RICHERT (1976) analysed surface sediment samples in the standard profiles (Fig. 1) between C. Bojador and Dakar from the shelf to the rise. He found diatoms only in some samples off C. Blanc and NW of Nouakchott, but mostly off C. Barbas. The assemblage consisted of 90 % Chaetoceras resting spores. Samples barren with regard to diatoms, sporadically contained faecal pellets with well preserved diatom frustules. Sometimes fibrills were present which possibly originated from Thalassiosira colonies. This result is very dissappointing because in plankton samples off NW Africa he found (RICHERT 1975) up to 14×10^5 diatom cells l^{-1}. Many of the dominant species therein have strongly silicified valves or resting spores.

Sediment filter

Interstitial silica gradients also indicate dissolution of siliceous material. However these concentrations are higher and the pH-values are lower than in near bottom waters. Therefore dissolution within the sediments is less effective than directly at the interface. Additionally more-resistant tests such as thick-walled compared to thin-walled diatoms, or in general radiolarians compared with diatoms, may be protected by selective dissolution and combined buffering. SCHRADER (1972) observed complete dissolution of diatoms and radiolarians below the upermost 30 cm of a sediment core off Morocco (2811 m water depth), with sponge spicules being more resistant.

Interstitial waters of strongly anoxic sediments with high organic matter contents and accumulation rates tend to preserve carbonates because they are saturated or even oversaturated with $CaCO_3$ within the sulfate reduction zone and below. A good example for excellent preservation are the varved basin sediments off California (SOUTAR 1971). Even off NW Africa interstitial waters in sediments with 1-4 % C_{org} and sedimentation rates of generally less than 50-100 mm/10^3 years, reducing conditions prevail below the uppermost centimeters. The regular decrease of the interstitial Ca^{2+} concentrations together with increasing alkalinities in these cores indicate even carbonate precipitation (HARTMANN et al. 1973, 1976). Again dissolution is possible within the uppermost oxic sediment centimeters, additionally to the above mentioned losses on the seabottom.

"Organic matter" is an extremely simplified term for a chemically very complex material, nevertheless some generalisations may be possible

After the reported rates of primary production off NW Africa ($0,27-0,67$ g C m^{-2} day^{-1}, WOOSTER & REID 1963; 0,28-0,59 SCHEMAINDA et al. (1975) or even 1-3 g C m^{2} day^{-1} off C. Blanc after HUNTSMAN & BARBER (1977) and calculations from surface sediments, less than 1 % pass our different filters.

Bacterial decomposition rates of organic matter in sediments depending on several factors including sedimentation rates decrease sharply below 5-10 cm (see direct measurements as in CHRISTENSEN & PACKARD 1977 an indirect geochemical conclusions as in HARTMANN et al. 1973, 1976). High sedimentation rates seem to preserve chemically more labile fractions of the organic matter.

Scanty direct measurements in interstitial waters tend to indicate phosphate dissolution, such of fish debris (E. SUESS, personal communication).

Quantitative effects of bioturbation are poorly known although the uppermost few centimenters off NW Africa are homogenized by this process. This indicates substantial activity of epi- and infauna in these sediments relatively rich in organic matter. Underneath individual biogenic tracks are arranged in tiered groups down to several centimeters. Therefore bioturbation may damage particles mechanically and favour dissolution in the uppermost centimeters but may protect them through downward mixing. Upward mixing also occurs, complicating the recognition of short-period events even in the surface sediments. (Observations off NW Africa: A. WETZEL, personal communication, general discussion BERGER, 1976)

<u>Consequences</u>

Due to these filters, upwelling indicators in sediments off NW Africa generally represent only a small fraction of the input from surface waters.

Mechanical destruction is highest on the shelf. Sorting of particles may also occur on the slope. Larger and denser particles are the more resistant ones.

This also holds true for chemical destruction. A succession of increasing dissolution effects seems to be:

? Fish debris (Phosphate) ?

$<$ Benthonic Foraminifera $<$ Planktonic Foraminifera $<$ Coccoliths (Calcite) $<$ Pteropods (Aragonite)

$<$ Radiolarians $<$ Diatoms (Opaline silica)

It may be expected that dissolution decreases with increasing sedimentation rates.

Upwelling indicators in sediments

Upwelling combined with high productivity is not restricted to coastal areas. On the other hand in coastal areas fertility may also increase near river mouths. This creates additional complications off NW Africa.

Organic matter

Organic matter content in sediments per se can be only a rough indicator of higher productivity because it depends on sedimentation rates in a complicated way. High rates may dilute the content but they protect the organic matter better against decomposition. Furthermore it is a well-known geological fact that fine-grained sediments are generally richer in organic matter due to greater adsorption capacities and the tendency to be both deposited under more quiet conditions. Accumulation rates of organic matter generally could be better indicators provided that sediments with similar grain size distributions, sedimentation and diagenetical situations can be compared. Off NW Africa there is a trend of increasing accumulation rates of organic matter from North to South, for example in Holocene sediments of 2000-2600 m water depths from about 10 mg C_{org} cm^{-2}/1000 years at latitude 25°N to 150 at 16°N (MÜLLER 1976 and personal communication). This seems to indicate an increase of productivity from North to South, but certainly input of clay by the Senegal river and better preservation of organic matter in these faster accumulating fine-grained sediments are additional factors.

Diagenetic products such as pyrite or phosphate enriched in sediments with higher organic matter content could not be used as upwelling indicators in younger sediments off NW Africa.

Metals

BOSTRÖM et al. (1974) compared average contents of elements in planktonic matter, shales and sediments from the high productivity region of the equatorial Pacific and they deduced the importance of biological contributions of elements like Cu, Ni, Ba. Zn and Pb are suspicious, too. HARTMANN et al. (1976) could not detect in surface sediments off NW Africa higher contents of these elements and no correlations for example between Cu and Zn and organic matter. SCHÖTTLE (1977) reports relative enrichment of Zn off the Senegal mouth, likely explained by a higher input of clay minerals together with organic matter. After LANGE (1975) these clays show high contents of Montmorillonites and specific surface values. Slightly increased contents of non-detritic Cu and Ni off C. Barbas could eventually be attributed to higher productivity. Relations between planktonic matter and metals, the influence of clay minerals and hydroxides during their transfer to the sediments and diagenetical changes are insuffiently well known to use these metals as upwelling indicators off NW Africa.

Barium, however, may have possible value as an upwelling indicator. The well known relationship with siliceous planktonic organisms (ARRHENIUS 1963, Diatoms: E. SUESS, personal communication) and the fact that Barium is easily precipitated together with Sulphate should be investigated off NW Africa.

Biological hard particles

As mentioned above, coarser shells in the sediments are in general more suitable to investigate possible upwelling relationships because of their increased resistance against mechanical or chemical destruction. Therefore most of our results are based on quantitative coarse grain component analysis (Fractions $>$ 63 µm, SARNTHEIN 1971, DIESTER-HAASS et al. 1973, DIESTER-HAASS 1975-1978). Some additional information from the silt fractions (2-63 µm) are given by FÜTTERER (1977). Sand contents vary considerably between $>$95 % on the shelf and the upper slope, to $<$5 % on the lower slope and rise, but within these environments, too. Silt normally is represented between 40-60 %, clay again varies between about $<$5 % (on the shelf and upper slope) and 50 %.

Coarse grain analysis of biogenic contributions, therefore has to take into account errors if only small quantities of sand grains are available in surface samples. Siliceous tests for example maximally reach 6 % of the sand fractions off NW Africa (DIESTER-HAASS 1975) and contribute less than 1 % to the silts (FÜTTERER 1977). Therefore single abundance figures are less reliable than trends.

Fish debris

Surprisingly, few fish remains were found off NW Africa (DIESTER-HAASS) with a possible exception of off 18°N, where MIRO (1973) found 2-3 % fish debris in surface sediment fractions $>$40 µm. There seems to be no other explanation for this scarcity other than chemical destruction within the uppermost sediment centimeters.

Siliceous shells

Similar dramatic losses of opaline silica shells off NW Africa were mentioned while discussing the different filters. Therefore, the presence of radiolarians or diatoms alone may indicate originally increased silica input, i. e. increased productivity. Dissolution in interstitial waters then could be diminished by buffering effects protecting more resistent forms. DIESTER-HAASS (1978) reports several percent diatoms and radiolarians in the fractions >40 μm of some surface samples between 18 and 22°N.

Aragonite shells

Pteropod shells are nearly absent in Holocene sediments off NW Africa. Therefore exceptionally the relations between water temperatures and volumes of protoconchs or dominance/diversity ratios of Pteropod assemblages could only be used in a few cases (DIESTER-HAASS & van der SPOEL, 1977).

Calcitic shells

Increased productivity of planktonic foraminifera is indicated by higher sedimentation rates of their tests on the NW African upper slope between 20°N and 24°N (DIESTER-HAASS 1976). An attempt has been made by DIESTER-HAASS (1977) to use the radiolarian/planktonic foraminifera ratios in surface samples. Again this area was singled out. This ratio, however, cannot be used uncritically because calcite dissolution influencing the ratio, too, depends on organic matter contents and sedimentation rates. Sorting effects may also be involved.

Planktonic/benthonic foraminifera ratios generally increase with water depth of the sediments, mostly due to decreasing benthos abundance. Variations of this ratio in similar water depths occurring off NW Africa indicate lower ratios in areas with higher productivity (BERGER et al. 1978, DIESTER-HAASS 1978). This may be attributed to higher food supply to benthonic organisms, and, indeed, sometimes other benthonic groups like echinoderms also seem to be more abundant there. Once again, higher organic matter contents may influence the ratio by dissolving planktonic foraminifera tests more easily than benthonic ones.

Species analyses

Diatom life assemblages off NW Africa unfortunately include no index species for upwelling areas in spite of high diversity values (SHANNON-factors around 2.5, see RICHERT 1975). Most of the species are cosmopolitans with high ecological tolerances. However, none of these features could be evaluated from surface sediment samples because of the losses passing through the above mentioned filters.

Planktonic foraminifera life assemblages were investigated in detail by THIEDE (1975, 1977) and were compared with burial assemblages on the continental margin from western Europe to about 20°N. He tried to quantify relationships between these surface sediment assemblages and sea surface winter and summer temperatures (and winter salinities) using the statistical methods from IMBRIE & KIPP (1971), together with the taxonomic framework from KIPP (1976).

In Spite of 1) faunal specialisations in marginal water masses, 2) the complicated hydrography in Eastern Boundary Current regions including seasonal differences caused by trade winds etc. and 3) filter effects mentioned above, several climatic assemblages could be identified: Polar to temperate assemblages together with subtropical and transitional assemblages and negatively tropical assemblages illustrate cooler Canary current temperatures from Portugal to C. Blanc. Special features between C. Blanc and about 25°N point to additional upwelling effects.

PFLAUMANN (1975) used temperature dependent assemblages from BE & HAMLIN (1967) and BE & TOLDERLUND (1971) in surface sediment faunas around 16°N. He found indications for lowered temperatures in water masses around the shelf edge, again a possible indication of upwelling effects.

Once again filters may disturb some results. Planktonic foraminifera living in cooler waters normally are thick-shelled and therefore more suitable to escape dissolution.

No detailed floral analysis of coccoliths exists from the NW African continental margin. One of the cool water species, Coccolithus pelagicus, is concentrated in the coarse silt fraction (20-63 µm) and enriched in surface sediments on the lower slope and rise off C. Barbas and C. Blanc. Again it is difficult to discriminate between effects of the Canary current and true upwelling (FÜTTERER 1977).

Isotopes

BERGER et al. (1977) used the stable carbon composition of the planktonic foraminifera Globigerinoides ruber in sediments off C. Barbas (2066 m water depth). $\delta^{13}C_{PDB}$-values are lower during periods of increased upwelling.

Regional and Geological Comparisons

Comparing sediments from coastal upwelling areas off NW Africa and off SW Africa (Table 1), cool water planktonic foraminifera assemblages are the most reliable indicators. Many other sedimentological and biological indicators are applicable if upwelling is persistent and highly effective as off SW Africa. However, in other areas such as off NW Africa, these indicators are only convincing if many factors can be combined after careful examination of sedimentation regimes. It appears to be easier to derive special features in sediments indicating upwelling from hydrographically known areas than to deduce less dramatic upwelling areas only from sediments.

Nevertheless the criteria mentioned in Table 1 could be applied in sediments from gravity cores and from the Deep Sea Drilling Project off NW Africa. Table 2 illustrates that increased upwelling occurred at the continental margin in glacial periods of the Pleistocene and upwelling with approximately the same intensity as present during interglacial periods. Tertiary sediments off C. Bojador revealed less intense upwelling during Late Pliocene, but a peak during Early Miocene.

Table 1

Coastal upwelling and sediments

Indicator	NW Africa (This paper)	SW Africa (see DIESTER-HAASS 1978)
Organic matter content	?	+ (Extremely high)
Phosphorites	–	+
Metals	? Cu ?Ni ?Zn	?Ni ?Zn +U
Barium	Not investigated	no information
C-Isotopes	$\delta^{13}C$ lower in Planktonic foraminifera tests	no information
Fish debris	–	+
Opaline silica tests	? (+)	+ (Extremely high diatom contents)
Calcitic tests Sedimentation rates	? (+)	no information
Radiolarian/planktonic foraminifera ratio	? (+)	+
Planktonic/benthonic foraminifera ratio	? (+)	?
Cool water assemblages		
Planktonic foraminifera	+	+
Coccoliths	? (+)	no information

Table 2

Neogene upwelling periods off NW Africa

	Million years	Intensity	Literature
	0		
Pleistocene			BERGER et al. (1978), CROWLEY (1976), DIESTER-HAASS (1977, in press), DIESTER-HAASS et al.(1973), GARDNER & HAYS (1976), LUTZE et al. (in press), McINTYRE et al. (1976), MOLINA-CRUZ & THIEDE (in press)
Glacial		++	
Interglacial		+	
	2		
Pliocene			DSDP Leg 47a Site 397 (DIESTER-HAASS, in press)
Late		Decreasing	
Early		–	DSDP Leg 47a Site 397 (DIESTER-HAASS, in press)
	5		
Miocene			DSDP Leg 47a Site 397 (DIESTER-HAASS, in press)
Late		–	
	12		
Middle		–	
	16		
Early		++	DSDP Leg 41, Site 369 (DIESTER-HAASS, in press),(SARNTHEIN, in press)
	22,5		

(Deep Sea Drilling Project Sites 369 and 397 are situated off C. Bojador)

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